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MERCURY IN AN ENCLOSED CHAMBER AS A HIGH SPEED ELECTRICAL CONTACT

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AND
J. H. FISHER

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Submitted in partial fulfillment
of the requirements
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ELECTRICAL ENGINEERING

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IN

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from the

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PREFACE

An investigation by Shults (1) showed the practicability of mercury in an enclosed chamber as a high speed electrical contact. He was able to pass fifty amperes at high rotational speeds.

The authors felt that further investigation was desirable. Professor C. V. O. Terwilliger, Chairman of the Department of Electrical Engineering of the United States Naval Postgraduate School, concurred and approved the inquiry as a thesis project.

Accordingly, this investigation was conducted at the United States Naval Postgraduate School, Monterey, California, during the academic year 1952-1953.

The authors wish to acknowledge the introductory study and continuing interest of Commander Roy G. Shults, United States Navy, the encouragement and advice of Doctor Terwilliger, the splendid workmanship and constant help of Mr. Joseph Octavek, leadingman of the Postgraduate School Machine Shop, and the cooperation and material assistance of the Overhaul and Repair Department, United States Naval Air Station, Alameda, California.

Clifford Edwin Olsen
John Herbert Fisher

Monterey, California
May 18, 1953

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SUMMARY

A high speed electrical contact employing mercury in an enclosed chamber was designed, manufactured, and tested under varying conditions of atmospheric pressure, current flow, and rotational speed. This study was conducted to determine the practicability of such a device.

The device was found to be superior to a slip ring and carbon brush. The voltage drop across the contact was independent of speed, reduced pressure, and linear with respect to current. A voltage drop of only 0.17 volt at three hundred amperes was achieved. The torque, weight, and space requirements are greatly in favor of the mercury contact. The voltage drops, though small, are highly oscillatory due to variation in contact resistance.

CHAPTER I

APPARATUS

Further investigation of Shults' device required that a set of conditions be decided upon and that these conditions be such that time and laboratory facilities would permit their accomplishment. Since his device, while not restricted to aviation use, was intended as a partial solution to the high altitude brush problem, as reviewed by Morris (2), it appeared logical to consider duplication of operating conditions for aircraft electrical machinery as satisfactory for proving the worth of the contact. These conditions include altitude, temperature, position, humidity, current, and speed.

Upon reviewing these conditions, it was immediately evident that they could not all be attained nor were they all important. For instance, temperature depends upon the location of an electrical machine. If it is in the nacelle of an aircraft it has access to as much cooling air as required. Therefore, temperature as an imposed condition was ruled out, but would be observed closely. Position would require an expensive gimbal arrangement and was considered unimportant since centrifugal force would retain the mercury around the periphery of the contact regardless of position. Unless a relatively large altitude chamber could be used, humidity would be extremely difficult to control. Since the vapor pressure of mercury is relatively low at the temperatures involved, humidity was assumed to have small effect on the device. Current was chosen to have a value sufficiently high to demonstrate the practica-

bility of the device as a transmitter of power - - - 300 amperes. Altitude was selected near the ceiling of present aircraft - - - 60,000 feet. Speed was selected high enough to prove the contact a high speed device - - - 12,000 revolutions per minute. These goals could be attained using laboratory facilities and properly designed test apparatus.

The altitude requirement could only be met using the laboratory facilities available by a small chamber. If the power unit was enclosed within the chamber, sufficient heat dissipation might be difficult. Mounting the power unit outside the chamber presented the problem of transmitting torque through the wall of the chamber while maintaining the chamber sufficiently airtight to permit evacuation to approximately five centimeters of mercury. Consultation with members of the mechanical engineering department led to the conclusion that if a shaft were used to transmit torque through the wall two methods of sealing were possible; either a sealing metal diaphram which rode on the shaft could be used or the clearance made sufficiently small to allow controlled leakage. The diaphram was a special order item of elusive origin. The controlled leakage required a more powerful vacuum pump than the standard chemical laboratory type. Hence another solution was sought and found in the use of an aviation hydraulic motor, bolted with an airtight gasket to the outside of the chamber. The shaft seal built into the hydraulic motor then acted as an air seal for the chamber. The motor could be driven by a hydraulic pump in turn driven by an

electric motor. This solution of the drive system established the design of a relatively small chamber holding only a speed changer, brush system and the high speed electrical contact.

The brush system was designed first since the brush holders would be bulky in size due to the large brush contact area, six square inches, required for 300 amperes current. This governed the chamber size to a great extent. The design is shown in Figures 1 and 2.

Since the contact used by Shults had operated very satisfactorily, his design was followed closely and advantage was taken of the defects he reported and changes made in structural strength to permit high speed. The shaft size and contact surface were increased for higher currents. The greatest change in design was the insertion of a sealed roller bearing in the contact chamber wall where it rotated about the fixed shaft.

This bearing was pressed on a fiber, insulating sleeve which in turn was pressed on the fixed shaft. Shults had used a fiber bushing with close tolerance to the shaft in place of a bearing. This wore and eventually leaked mercury. It was felt that the bearing would be better because it would support that portion of the cylinder firmly and prevent any whipping due to the cylinder and shaft being cantilevered, and the bearing being sealed would reduce leakage of mercury. The machinist suggested and manufactured the cylinder so that the wall in which the bearing was mounted was made thicker and the inside extended to a close tolerance with the shaft, further guarding against mercury

leakage and damage to the bearing from mercury.

Gears were considered for the speed changer but were found to be expensive and time consuming to manufacture. The pulley assembly decided upon increased the rotational speed by a ratio of one to four. This permitted the hydraulic system to operate at approximately 80% full speed at 12,000 rpm.

This concluded the design of the machinery to be placed in the altitude chamber. The chamber was then designed to permit entrance of intelligence leads and air tubes. This chamber was a box made of one half inch steel plate with a plexiglass top supported by two steel rods to prevent collapsing. Ports were cut into the box for vacuum pump connections, voltmeter leads, current leads, controlled air leakage, and drive shaft. Rubber stoppers were used to seal around wires and glass tubes going through these ports. The hydraulic motor was sealed directly to the exterior of the box by use of an "O" ring gasket. Insulating sleeves were used around the current leads to prevent air leakage. Controlled leakage was used to maintain desired pressures.

The electric-hydraulic drive system used was entirely aviation equipment on loan from Overhaul and Repair, Naval Air Station, Alameda. The system consisted of a direct current motor, hydraulic pump, hydraulic motor, and a reservoir. A 24 volt, 96 ampere, 2¼ horsepower direct current motor was employed to drive a Vickers hydraulic pump. Power for the motor was obtained from the laboratory 30 volt motor-generator set. To rid the system of air and provide adequate hydraulic fluid,

a reservoir was placed on the low pressure line with a high pressure bleed into the reservoir. Speed control was obtained by a valve between the high and the low pressure lines of the pump, bypassing the motor.

Drawings incorporating the above designs were submitted to the machine shop for manufacture. They are shown in Figures 1 through 5. Not shown in these drawings is the current lead-in which consisted of a lug bolt with insulating sleeve connected to a bus bar to which the pigtails from the brushes were secured. Also a flat bronze spring riding on the end of the brass cylinder of the brush system was installed to facilitate measuring the voltages across the carbon brush system and across the mercury contact.

Materials furnished the machine shop included the roller bearings for the contact chamber and bearing mounts. These bearings were sealed, grease packed. While it was not known whether or not they contained high temperature grease, the decision to use them was made because of the relatively short duration of the tests and the difficulty in obtaining high temperature bearings.

While the above apparatus was being manufactured, a test bench was built and the wiring, vacuum pump and manometer, hydraulic system and the measurement equipment was installed.

The test bench was wired for 115 volt direct current, 30 volt direct current and 115 volt alternating current. The 115 volt direct current system was used to pass current through the contact. It required large size cables spliced into the main laboratory system in

the trench passing under the test bench. Plug in bus bars were made of brass flat bar to place the portable, 72 amperes, variable resistors in parallel. Switches were mounted for ammeter protection and main switching. The thirty volt system furnished power for the electric motor driving the hydraulic system and was also furnished with two switches, main and ammeter. The 115 volt alternating current system was brought to the bench for ease in using electric tools during the construction period and for operation of the strobotac used to measure speed and power to the vacuum pump.

After the altitude chamber with test apparatus was installed and operated, a modification was decided upon. The brush and brass cylinder assembly was removed and a second contact, similar in all respects except threads to the original, was manufactured by the machine shop and installed on the same shaft with the original contact. The second contact was manufactured with left hand threads in order that each contact would rotate in a tightening direction. The drawing is shown in Figure 6.

While the machine was being altered, the temperature measuring system was improved upon. Previously, measurements were made using a Weston Model 226, dial-type thermometer inserted in the fixed shaft to a point near the disk. A second hole was drilled in the new fixed shaft and thermocouples embedded. Copper-constantan was used for the thermocouples, ice water for reference, and a Leeds and Northrup potentiometer for measuring temperature.

A standard chemical thermometer, was placed inside the altitude

chamber in such a manner that it could be read through the plexiglass and the temperature of the air in the chamber recorded.

The meters used for measuring the voltages across the contacts were zero to one volt with 5000 ohms resistance. To verify the measurements thus obtained, a high resistance voltmeter, zero to three volt, was connected across both contacts and used to read the sum of the two one volt meters. These meters were carefully calibrated.

Photographs of the apparatus and test bench are shown in Figures 8 through 12. A schematic diagram of the altitude chamber with electrical, hydraulic, and air systems is shown in Figure 7.

A difficult problem worthy of mention was the containment of mercury in the rotating chamber at high speeds. Shults ran into this problem - - - his device threw mercury out through the threads where the two sections of the chamber were joined together. To avoid this, a gasket was called for in the design as shown in Figure 4. The machinist first used rubber for this gasket, and the machine was operated for several hours during the break-in period without leakage. Then a fine trace of mercury appeared across the plexiglass and box in line with the junction of the two cylinder parts. It was assumed that loosening had occurred during the rapid deceleration period when the brush system and hydraulic system presented high torque in a decelerating direction to the section of the chamber rotating freely with high inertia on the fixed shaft and coupled to the drive by the threads alone.

At this time the modification was completed and both the original

and the new contact were fitted with new rubber gaskets. Care was taken to bring the speed down slowly, but overheating occurred on the new contact, as explained in the following chapter, and the rubber gasket softened and permitted mercury to be thrown out. Both contacts had to be disassembled to remove them from the altitude chamber, so in spite of the fact that the original contact had not started leaking, both were fitted with soft copper gaskets. It was hoped that sufficient tightening would compress the gaskets against both parts of the cylinders. This failed immediately.

The machinist, Mr. Octavek, then elected to try ordinary paper gaskets. This proved satisfactory.

No doubt a better design could be found for joining the two parts of the cylinder. However, it was required that the joint be on the periphery to enable the disk to be slipped out, and that the parts be joined in such a manner that disassembly for inspection and installation in the altitude chamber was possible. This places the joint in a location where the centrifugal force of the mercury against the gasket causes sealing to be a very difficult problem.

CHAPTER II

PROCEDURE

The testing phase of the project investigating the high speed contact consisted of the break-in period, the test "runs" under simulated operating conditions, and the static tests investigating contact resistance.

Because of the carbon brush system installed, a preliminary break-in period was required. During this period the speed was varied in steps up to 8,500 rpm with frequent stops for brush sanding, brush pressure adjustment, tightening, etc. Maximum currents, limited by the brushes arcing, were passed through the chamber but because of fluctuation of voltage across the carbon brush system, only sporadic points could be obtained. During this period of break-in, the device was operated for long periods of time.

It became apparent during this break-in period that the brush system would never permit good results in testing. The brush pressure required to limit arcing was such that an arrangement for removing pressure at starting was necessary. In addition, arcing would take place at altitude, grow in magnitude to a point where burning of the brushes could occur, and persist until the current was removed. Even though the brushes were sanded to a close fit, these difficulties persisted and it was elected to modify the machine by replacing the brush system by a contact similar to the one being tested.

Upon installation of the second contact, a run was made at 8,000 rpm

using unequal quantities of mercury in the contacts to determine the heat generated due to friction. Nine cubic centimeters of mercury were placed in the new contact, referred to as the right contact, and the temperature rise noted. Inadvertantly, the contact was overheated. It was then realized that the heat flow was such that very high temperatures could be generated on the periphery of the contact where the friction occurred with a substantially lower temperature indicated on the thermocouple embedded in the shaft at a point near the disk. This overheating caused the rubber gasket used to seal the two sections of the chamber together to soften and permit mercury to be forced, centrifugally, past the seal, through the threads and out. Also, the bearing between the fixed shaft and the rotating chamber suffered from this high temperature. New seals were installed but it was not noticed until later that the bearing had been damaged.

Testing was done by turning the machinery up to a predetermined speed, holding all variables except one constant, and taking readings. In general, the runs were made at speeds from zero to 8,000 rpm, altitudes of sea level to 60,000 feet, and currents from 50 to 300 amperes in 50 ampere steps. Temperatures were observed closely during each run. Minimum amounts of mercury, six cubic centimeters, were used.

With the plexiglass top in place, the altitude chamber acted as an inefficient heat trap. A great amount of the heat generated by the machinery due to friction and current flow was effectively trapped within the chamber. Because of this, runs at specific speeds were conducted as

rapidly as possible to prevent overheating. It was well that this precaution was observed because, as mentioned above, the sealed roller bearing in the right contact dried out from the relatively high temperatures. During runs at 8,000 rpm, this bearing overheated causing the fiber sleeve on which the bearing was pressed to char and break.

After the runs were completed, or rather terminated due to the bearing failure, it was decided that sufficient data except for maximum speed had been taken. A series of static runs, zero speed, were then taken to investigate further the phenomenon of contact resistance ascribed to surface film on the mercury. The current and contact position were varied while temperature, time, and voltage drops were recorded.

CHAPTER III

DISCUSSION

As described in Chapter II, many different types of tests were performed. Some of the tests led to results which required analysis to varying degrees and therefore Figures 13 through 20 are included to show graphically the quantities involved.

In general, all tests showed the major factor in the voltage drop across the contact to be resistance at the surface between the mercury and the steel. It is convenient to ascribe to this contact resistance the properties of a thin film. This thin film probably exists as a layer of oxides and contaminants in the mercury, but perhaps it is a periodic failure of the mercury to reach sufficiently intimate contact with the steel due to surface tension.

Tests conducted under apparently identical conditions showed great differences in the amount of contact resistance. During a given run, this resistance sometimes changed in value but normally remained the same provided that the speed was not altered to such a degree that the distribution or turbulence pattern of the mercury was changed.

Those runs in which the current was held at a constant value and either the speed or altitude changed showed the voltage drop to remain substantially constant over all ranges of the variable. During starting when the mercury distribution changed from a pool at the bottom of the cylinder to an even distribution about the periphery, the voltage drop was oscillatory to a high degree. Stopping produced the same results.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Because the drive system did not permit rapid speed changes, it is not known what effect such speed changes would have. The failure of altitude to have an effect is not unexpected, however it was thought to be worthy of investigation because carbon brushes failed at low pressures.

It had been expected that speed would have two effects. First, the centrifugal force on the mercury due to the high rotational speeds would force the mercury into more intimate contact and would squeeze out the film by virtue of mercury's greater density and therefore reduce contact resistance. Secondly, the slippage of mercury past the steel surfaces would alter the film as new portions would be brought into contact and new turbulence patterns would be set up at each speed. Neither of these effects was noted.

Tests in which the speed and altitude were held constant and the current varied gave voltage drops across the contact which varied in the manner shown in Figures 13 through 15. The data shown in Figures 13 and 14 are typical of all runs of this type conducted. It will be noted that most of the curves have an average slope corresponding to a resistance of approximately 7×10^{-4} ohms. Figures 16 and 17 show this more clearly in that they have a voltage drop based on this resistance subtracted from Figures 13 and 14. These curves are substantially horizontal. It is believed that this resistance is that of the homogeneous parts of the contact but that the voltage drop due to contact resistance is constant for a given film with respect to

current. In some runs of this type contact resistance appeared negligible. Figure 15 contains curves of many runs of this character at 4,000 rpm and various altitudes. The small fluctuations in these curves are probably due to slight films forming and being removed. The apparent linearity of voltage drop in the homogeneous media with respect to current is to be expected. The failure of contact resistance to be proportional to current has been observed in such other contact devices as the carbon brush.

To gain a better understanding of the phenomena of contact resistance, further tests were conducted at zero speed and zero altitude. This reduced the number of variables to be controlled since it had been noted previously that contact resistance was independent of speed and altitude. The tests further confirmed the suggested theory of a film on the surface of the mercury, but gave insufficient evidence to relate voltage drop and temperature.

These tests were made using a constant current and recording voltage drop and temperature as functions of time. Temperatures recorded were those at the thermocouples and were undoubtedly considerably lower than those on the periphery of the contacts since steady states were not attained. The recorded data is plotted in graphs shown in Figures 18 and 19. The extreme oscillations appear to be caused by localized heating causing film breakdown. This film breakdown in turn causes a smaller voltage drop and less heat allowing the film to be reformed and the process to be repeated. The curves showing

no oscillations might be attributed to the contact having less film on the mercury initially and thus less localized heating. The recorded data of these tests differed so greatly in each run that conclusions as to the actual phenomena occurring were impossible.

The Liquid Metals Handbook (3) states that small quantities of magnesium added to mercury reduce the contact resistance and increase the mercury's ability to wet metals. This apparent correlation of wetting and contact resistance confirms the film and intimate contact theories. Twenty ppm magnesium were added to both contacts. Marked improvement was noticeable for a period of about one hour. Twenty ppm more were added to the left cylinder and again improvement lasted for about one hour.

However, it was noted, as shown in Figure 20, that if the device remained in one position for long periods of time that the magnesium had an effect. The zero angle for these curves is that at which the device had remained stationary over a weekend. Previous tests of this type had shown no dependence of contact resistance upon position flucuations had been completely random. These runs were conducted on different days with different rest positions confirming the belief that this phenomena is based on immersion over a period of time and not because of peculiarities of manufacture. A few revolutions were made before commencing the test to remove any films formed or displaced during the idle period. Long periods of contact apparently increase the ability of the steel to be wetted.

Temperature measurements were subject to great error. Because it had been expected that heat generation would be low enough to permit attainment of steady state temperature distribution, thermocouple location was not considered critical. However, when it became evident that local temperatures were exceeding those considered safe and that only short time operations could be conducted, it became impossible to attain sufficient accuracy to make quantitative results meaningful. The progressive failure of the bearing in the right contact resulted in local heating very close to the thermocouple and gave unusable, high temperature readings. Therefore, conclusions can be at the most qualitative. Heat generation due to friction increases with increased speed and mercury content. Shults (1) was able to operate for extended periods of time with air cooling directed on the contact. For this reason it is believed that provision for some method of cooling on any practical application would limit temperatures sufficiently.

Powdered graphite was introduced into the right cylinder to reduce the coefficient of friction within this cylinder and thus reduce the heat generated by friction. It is believed that it accomplished this purpose.

Of academic interest is the fact that ten millivolts were generated by slippage of the dissimiliar materials in the contact at high speeds.

CHAPTER IV

CONCLUSIONS

The overall result of this inquiry has been to establish further that the high speed electrical contact employing mercury in an enclosed chamber is a practical device.

In all cases the voltage drop across the mercury contact was considerably below that which could be expected from the conventional slip ring and carbon brush assembly. Under some conditions of contact resistance, it was possible to conduct three hundred amperes with a voltage drop of only 0.17 volts. It appears possible that inhibitors could be found that would permit extremely low linear voltage drops for a long period of time when introduced into purified mercury in a clean contact.

This voltage drop was found to be independent of both speed and altitude and linear with respect to current. A large portion of the voltage drop in most cases was found to be caused by contact resistance; this resistance was oscillatory and independent of speed, altitude, and current.

The torque requirement of this type contact is small. It was observed that the presence of mercury within the cylinders caused very little increase in the input drive power. This torque is much smaller than that required to overcome brush friction.

The size and weight of mercury contact is comparable to that of a

slip ring alone. The space and weight of the carbon brushes and holders are saved by use of this type contact.

It is believed that with the cooling normally available in any application, temperature would not be a limiting factor.

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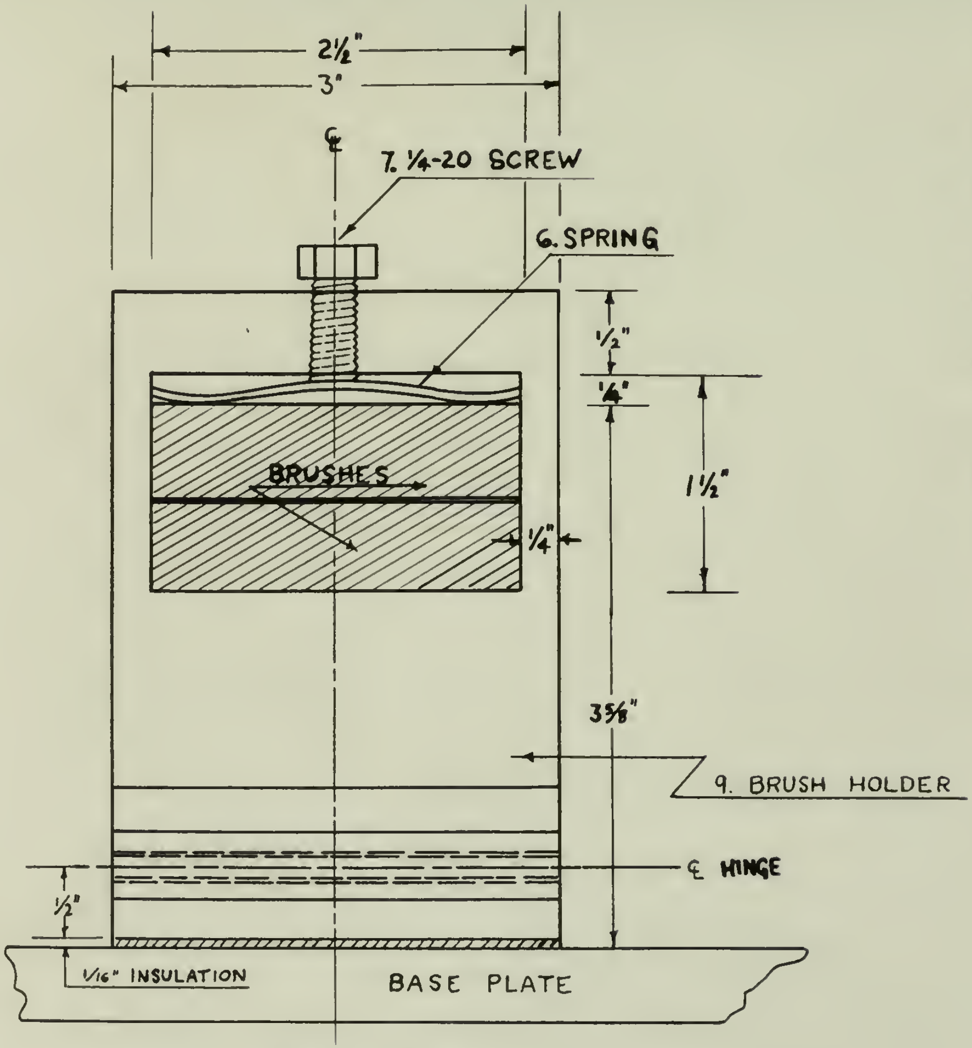
3. Atomic Energy Commission. Liquid Metals Handbook. Washington, U. S. Government Printing Office, 1950.



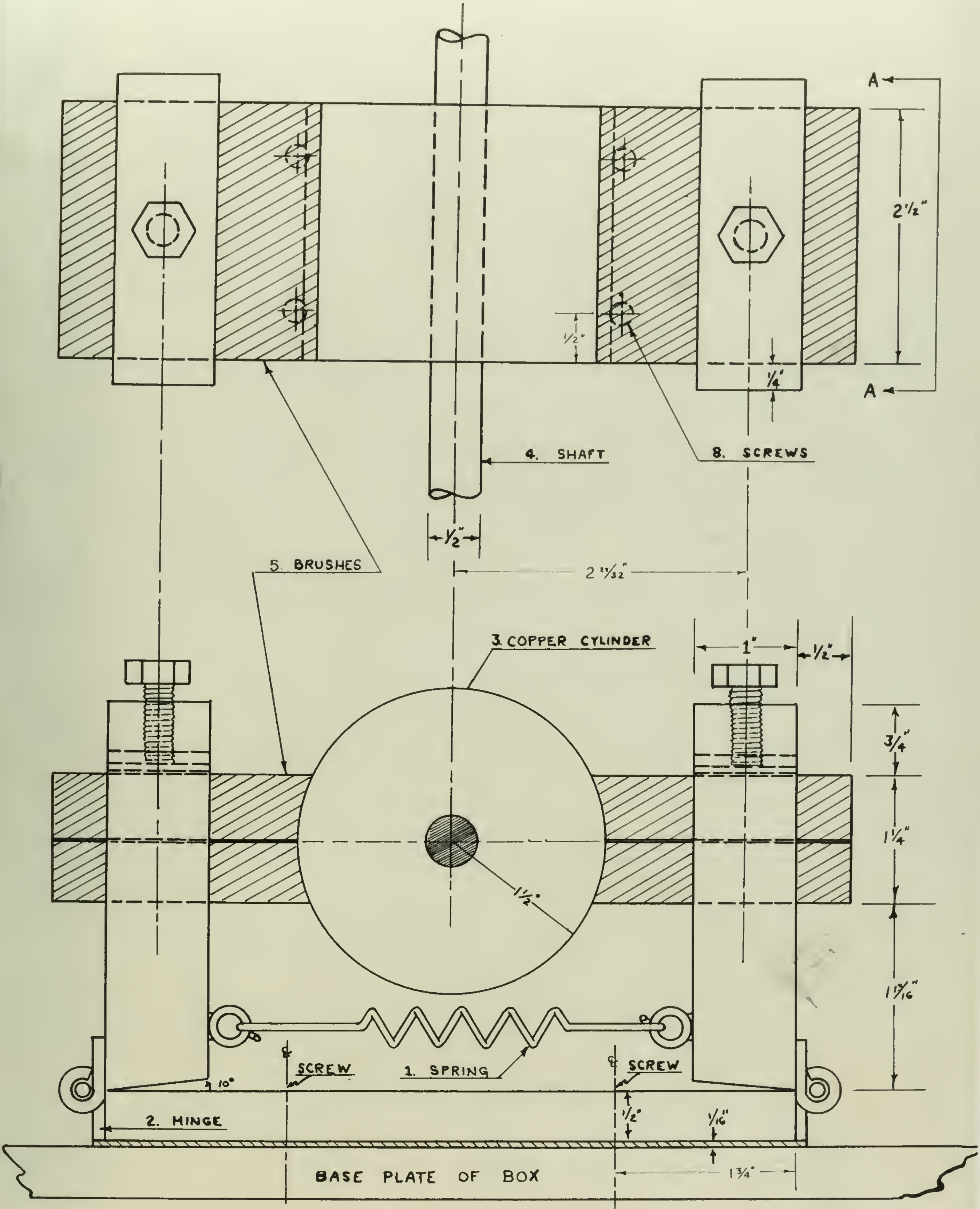
ELEVATION A-A

NOTES

1. SPRING — SELECT TO GIVE 2 LBS. BRUSH PRESSURE (TOTAL).
2. HINGE - ANY SUITABE READY-MADE HINGE.
3. COPPER CYLINDER — SET-SCREW TO SHAFT.
4. SHAFT - CARBON STEEL.
5. BRUSHES - FURNISHED, FIT TO CYLINDER.
6. SPRING — BRONZE OR SUITABLE MATERIAL.
7. SCREW - ¼-20 OR ANY SUITABLE SIZE.
8. SCREWS - PRESSED FIBRE, FURNISHED.
9. BRUSH HOLDER — CARBON STEEL.

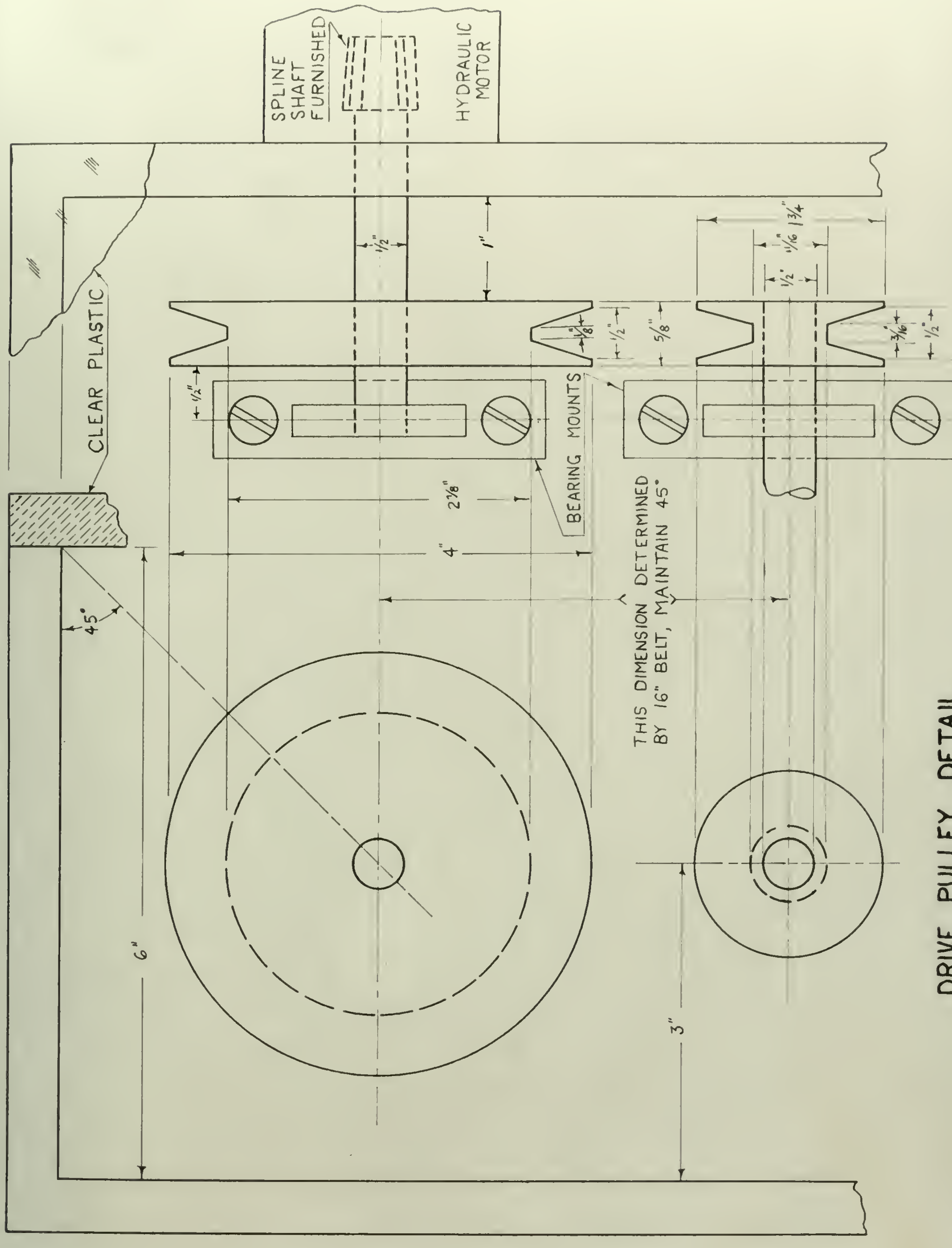
BRUSH HOLDER DETAIL

FIG. 1



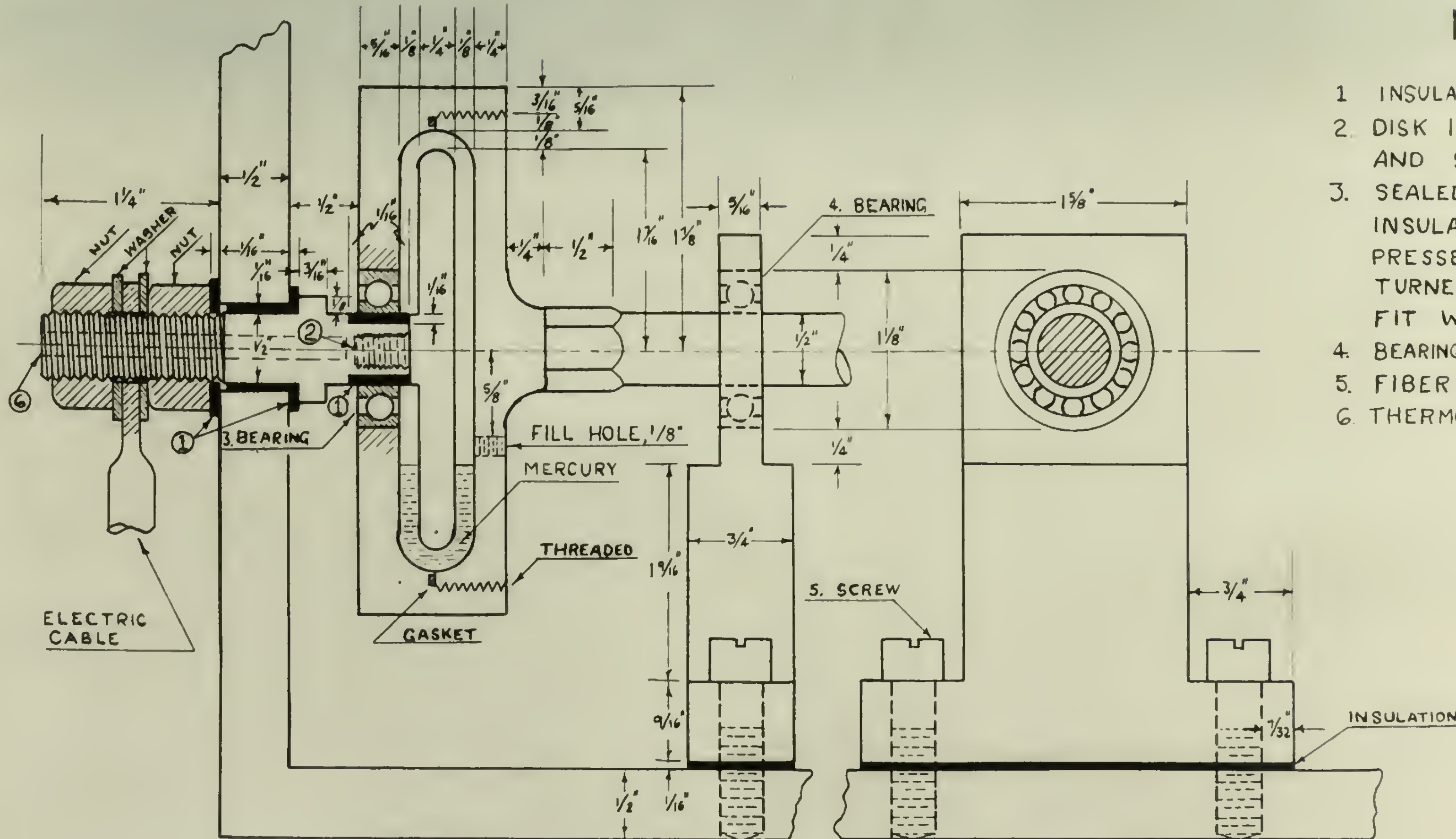
BRUSH HOLDER DETAIL

FIG. 2



DRIVE PULLEY DETAIL

FIG 7



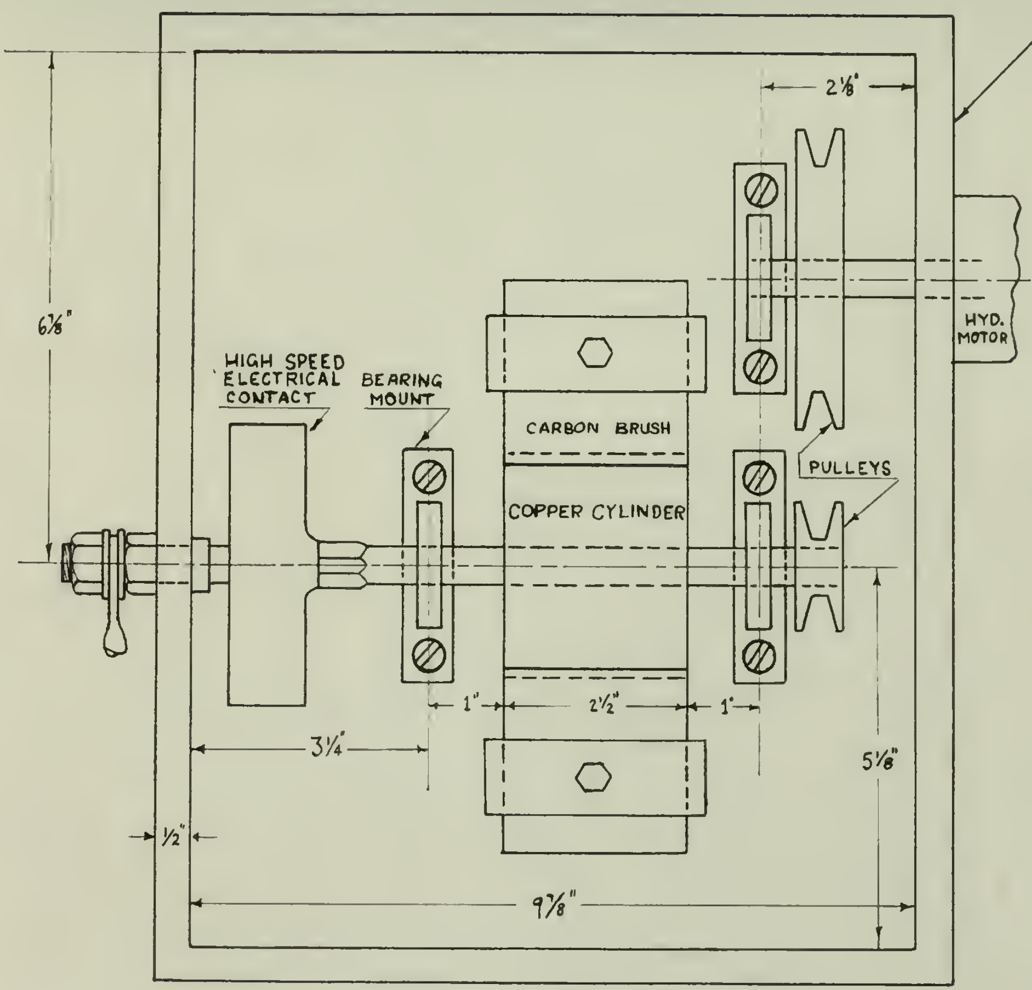
HIGH SPEED ELECTRICAL CONTACT DETAIL

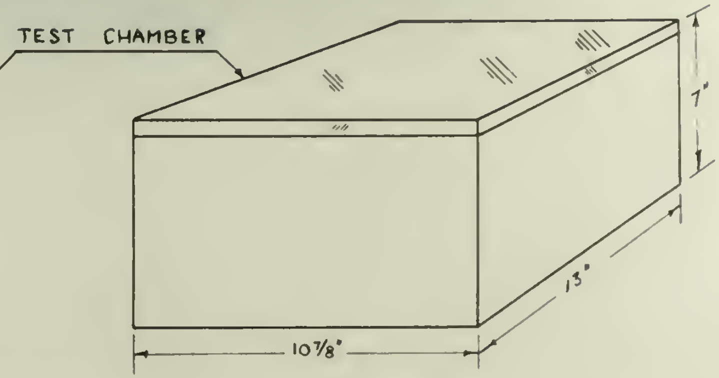
BEARING MOUNT DETAIL

FIG. 4

NOTES

1. INSULATING WASHERS & SLEEVES.
2. DISK IS THREADED, 1/4-28, AND SCREWED INTO SHAFT.
3. SEALED 1/2" BEARING, FURNISHED. INSULATING SLEEVE TO BE PRESSED ON SHAFT AND THEN TURNED DOWN TO A TIGHT FIT WITH BEARING.
4. BEARING, 1/2", FURNISHED.
5. FIBER SCREW FURNISHED, 5/16".
6. THERMOMETER HOLE, 9/64".



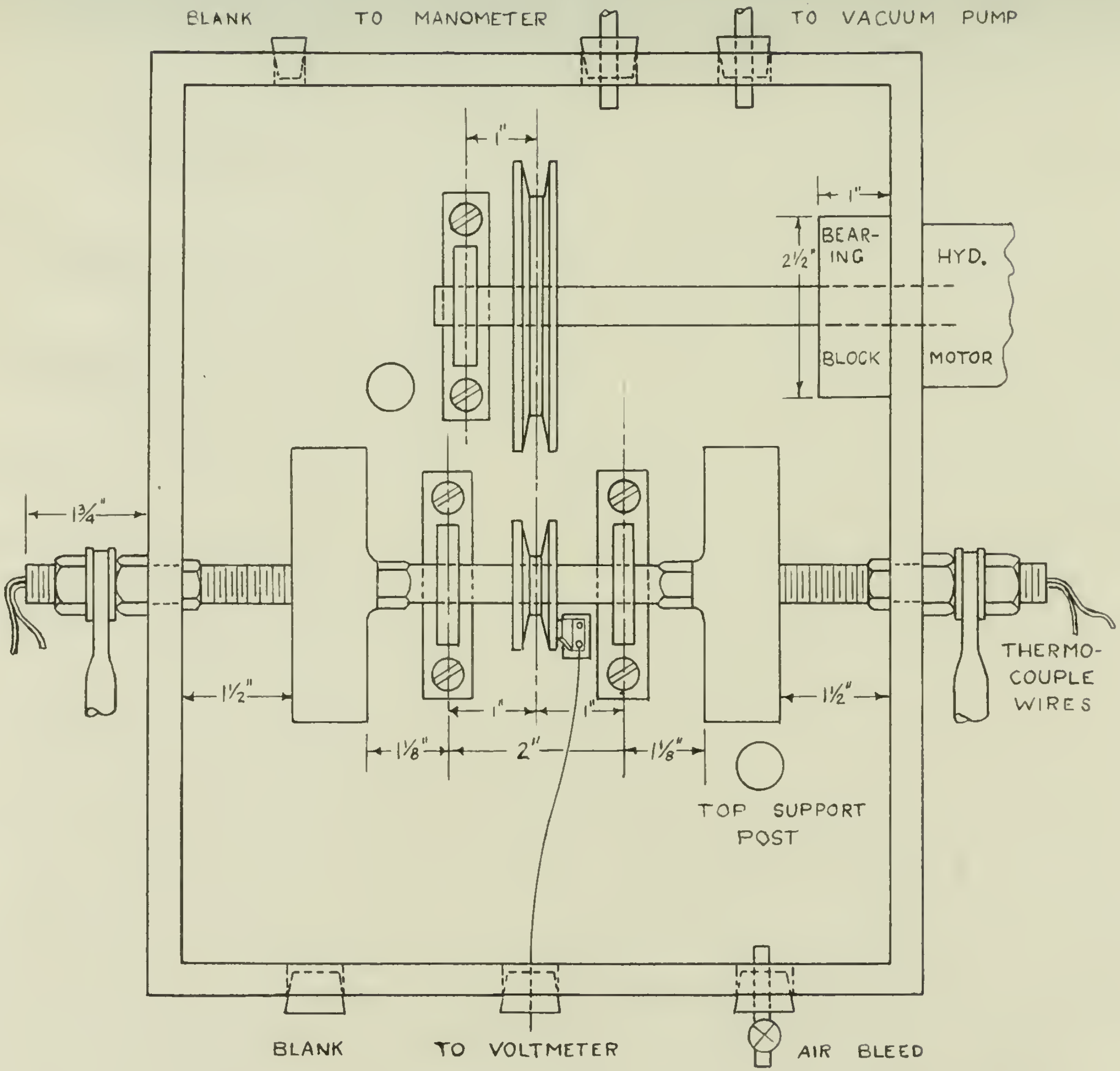


NOTES

1. THE TEST CHAMBER IS A 1/2" STEEL BOX, EITHER WELDED OR SCREWED TOGETHER, WITH A 1/2" CLEAR PLASTIC TOP.
2. THE HYDRAULIC MOTOR WILL BE LOCATED AFTER A 16" BELT IS TRIED ON THE PULLEYS TO ESTABLISH CENTER-LINE DIMENSIONS.
3. DETAIL DRAWINGS OF PARTS FOLLOW.
4. SCREW SIZE AND SPACING, MATERIALS, GASKETS, SOME DIMENSIONS, AND ALL OTHER MISSING DETAILS WILL BE DETERMINED BY CONSULTATION WITH THE MACHINIST. THIS INCLUDES ALL PORTS INTO BOX FOR ELECRICAL INPUT AND INTELLIGENCE LEADS.
5. THE ELECTRICAL CONTACT WILL TURN 12,000 RPM.
6. THE TEST CHAMBER WILL BE REDUCED IN PRESSURE TO 2.16" MERCURY OR 60,000 FT. ALTITUDE.
7. THE CURRENT WILL BE 300 AMP. MAX.

TEST CHAMBER & EQUIPMENT

FIG. 5

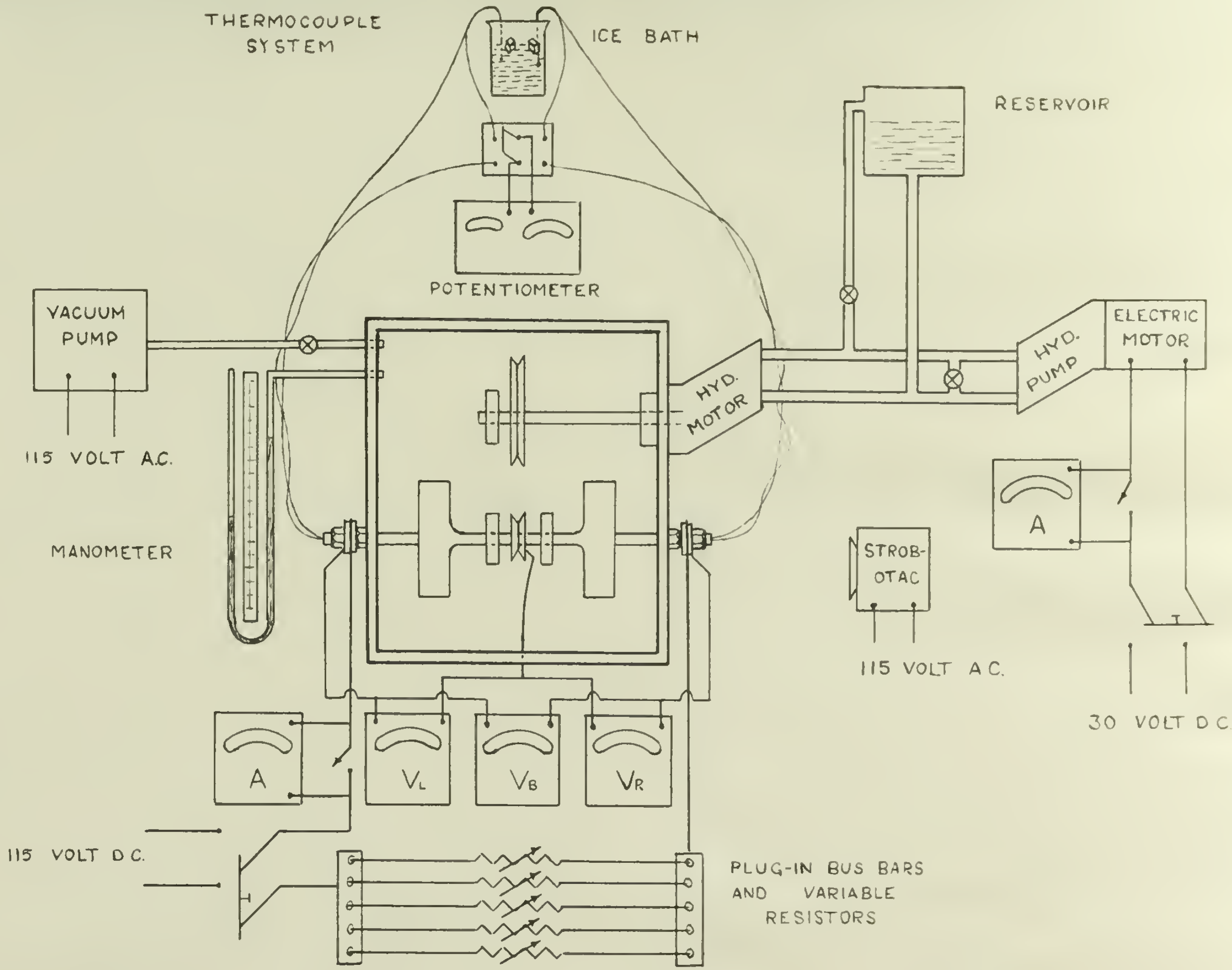


NOTES

1 THE BRUSH ASSEMBLY WILL BE REPLACED BY A SECOND CONTACT, IDENTICAL TO THE ORIGINAL EXCEPT FOR LEFT-HAND THREADS.
2 A BEARING BLOCK IS PLACED ON WALL AS SHOWN TO SUPPORT SHAFT.
3. A BRONZE SPRING IS INSTALLED, RIDING ON SMALL PULLEY AND INSULATED FROM BOX.
4. FIXED SHAFT IS THREADED WITH TIGHTENING NUT TO PERMIT INSTALLATION AND REMOVAL.
5. A HOLE, AS SMALL AS PERMISSIBLE WILL BE DRILLED IN THE NEW FIXED SHAFT FOR THERMOCOUPLE INSTALLATION.
6. POSTS OF 1/2" STEEL ROD WILL BE INSTALLED AS SHOWN TO SUPPORT PLEXIGLASS TOP

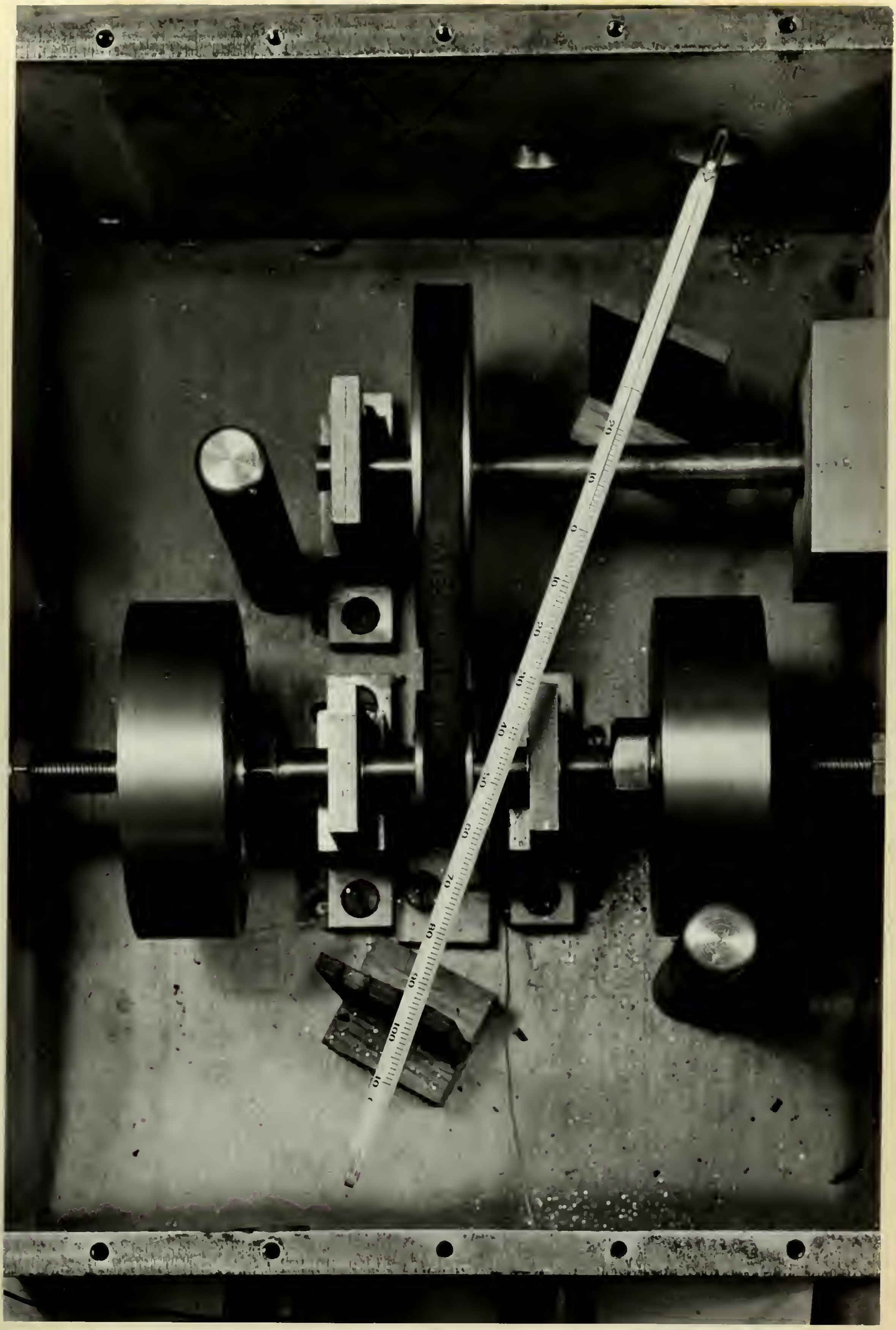
TEST CHAMBER - MODIFIED

FIG. 6



SCHEMATIC OF TEST APPARATUS

FIG. 7



Altitude Chamber (Top View)

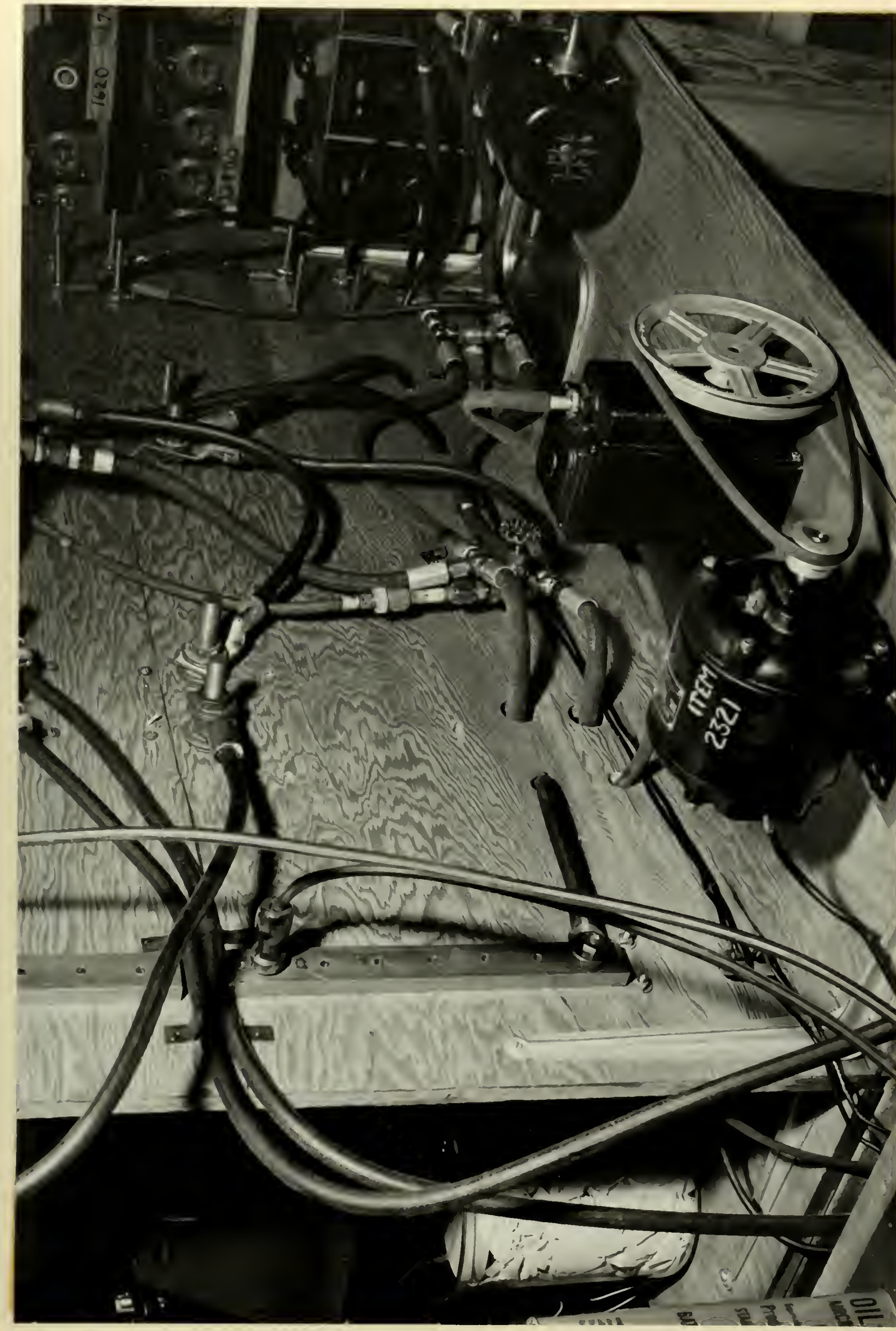
Fig. 8

Test Apparatus (Top View)

Fig. 9

Test Apparatus (Front View)

Fig. 10

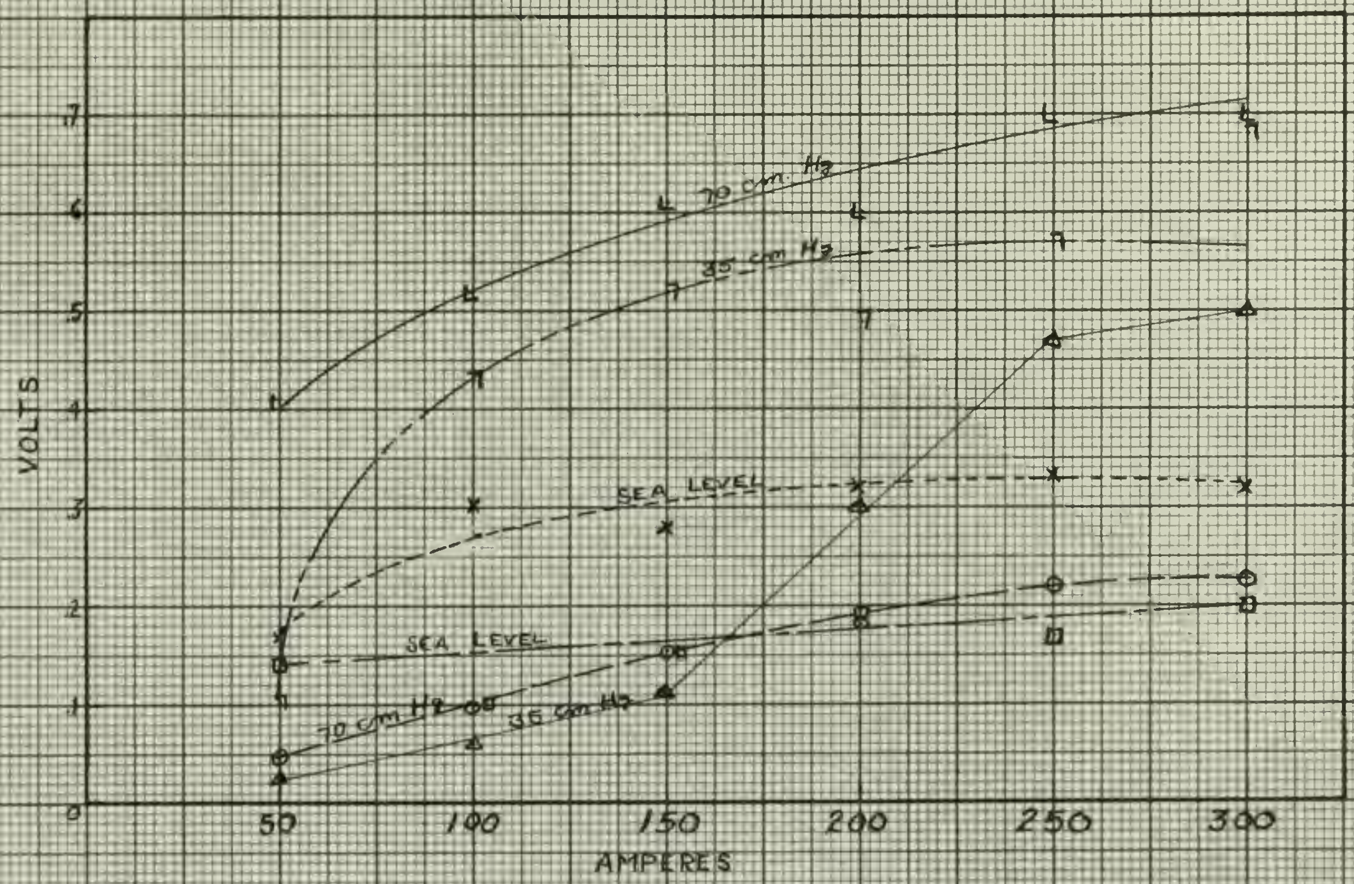


Test Apparatus (Back View)

Fig. 11

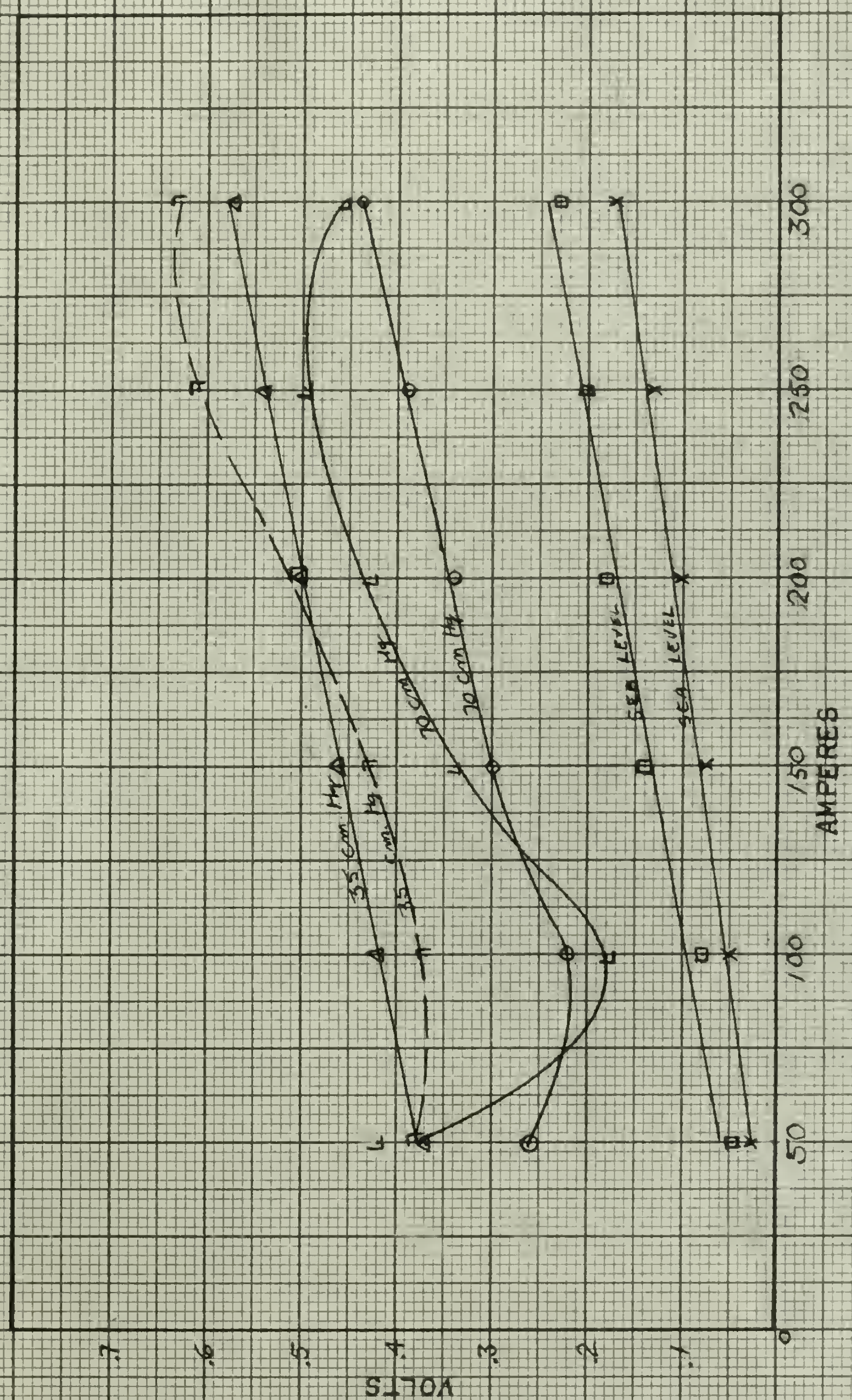
Test Apparatus (Oblique View)

Fig. 12



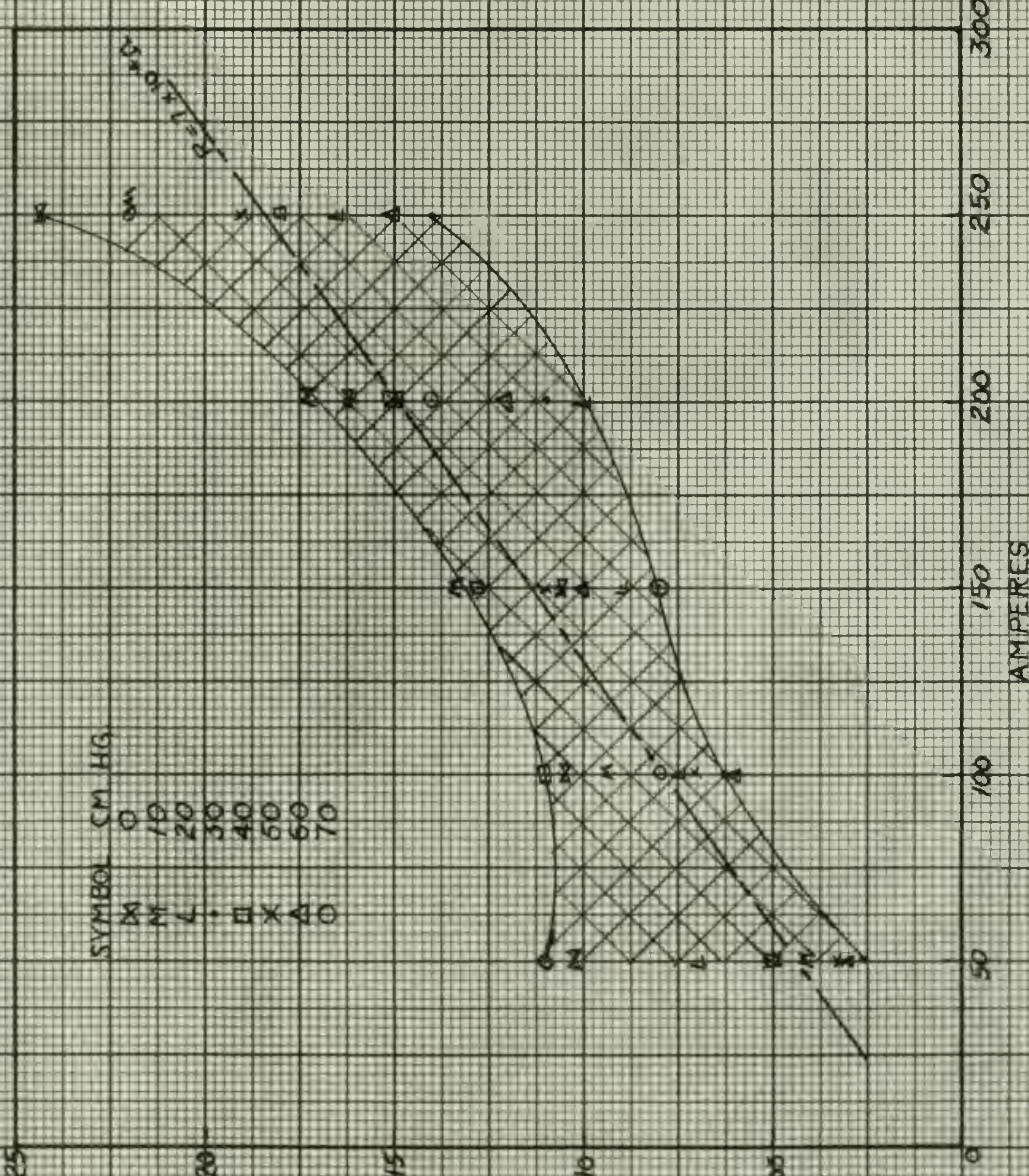
VOLTAGE DROP VS CURRENT AT 6000 RPM

FIG. 13



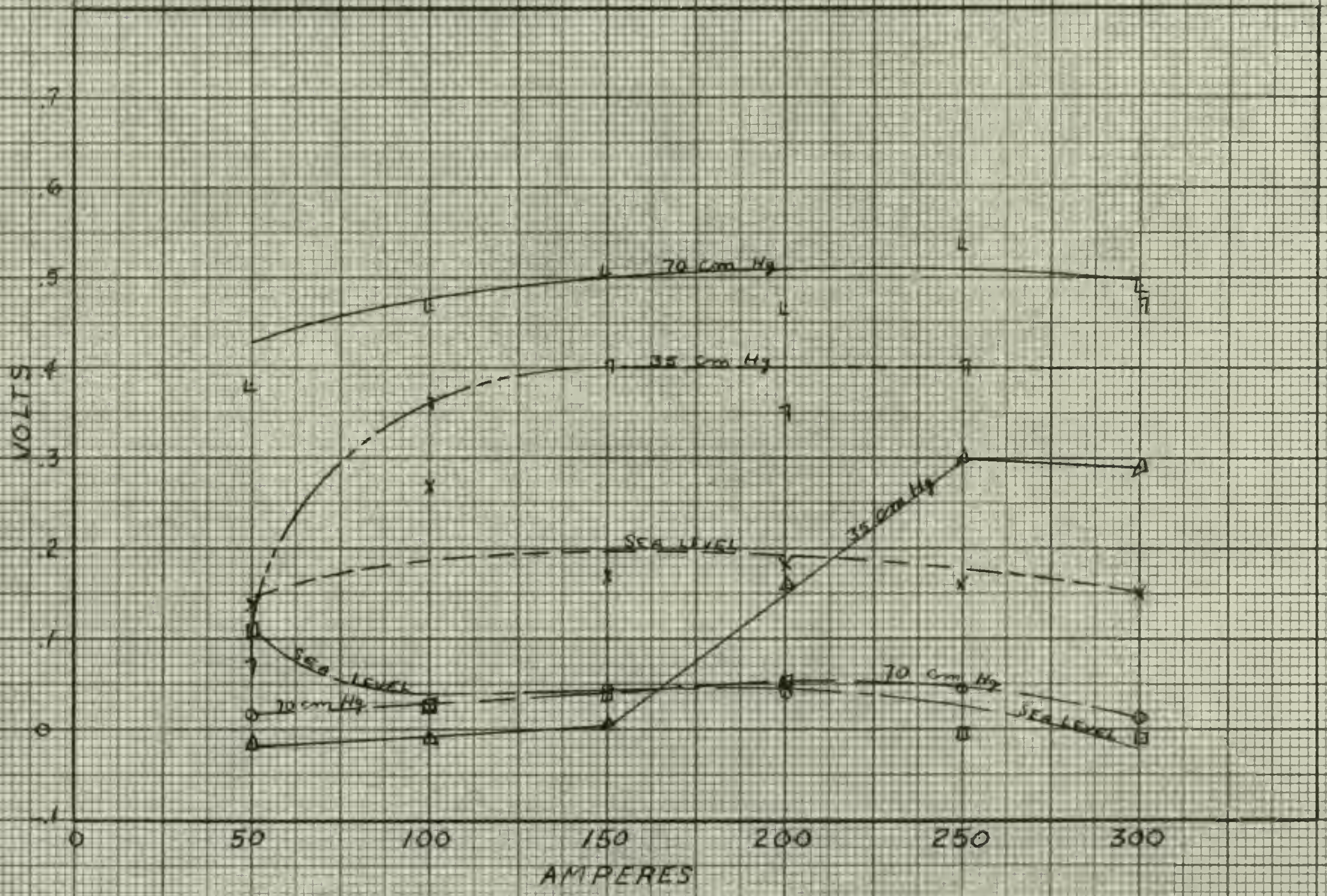
VOLTAGE DROP vs. CURRENT AT 8000 RPM

FIG. 14



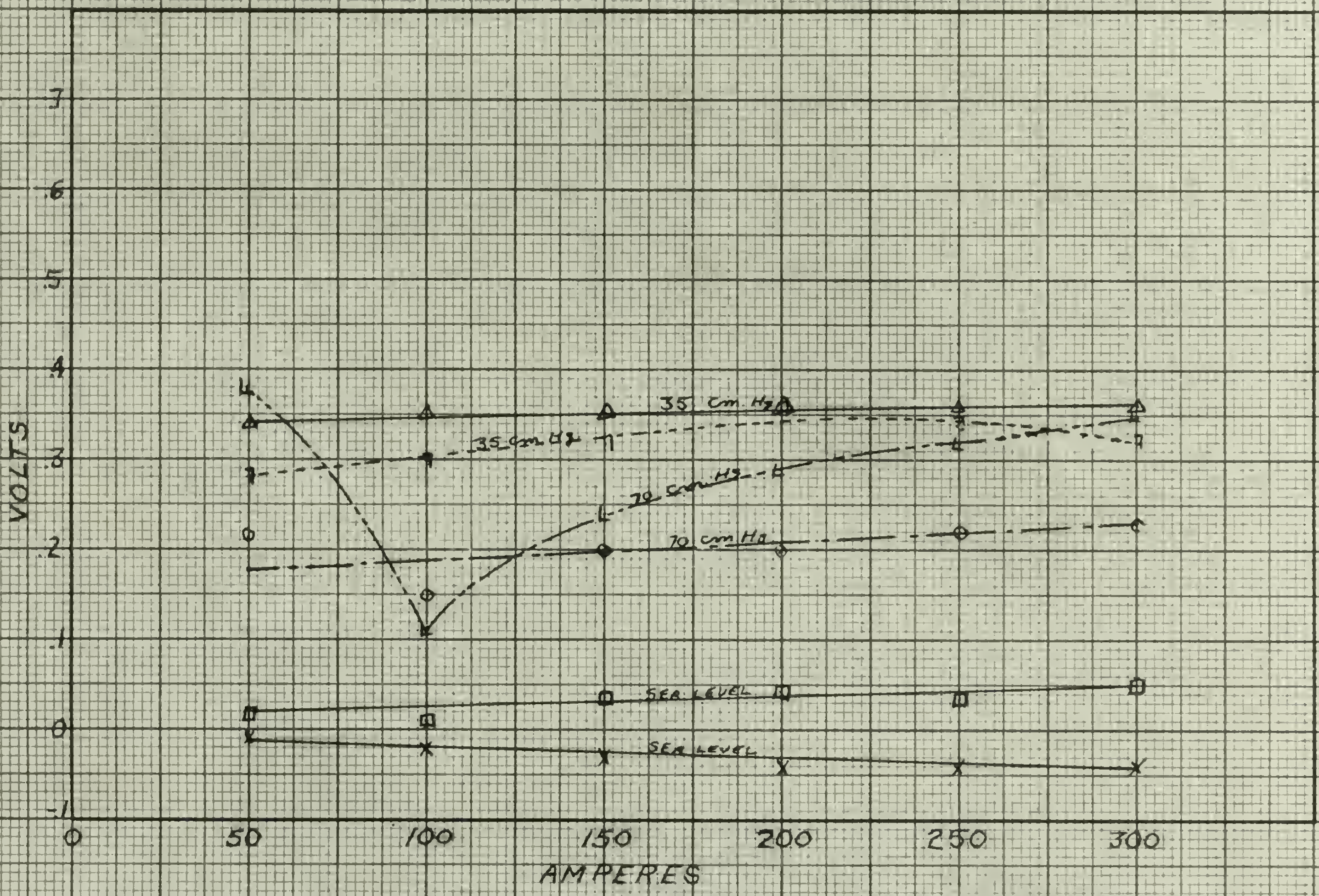
VOLTAGE DROP VS. CURRENT AT 4000 R.P.M

FIG 15



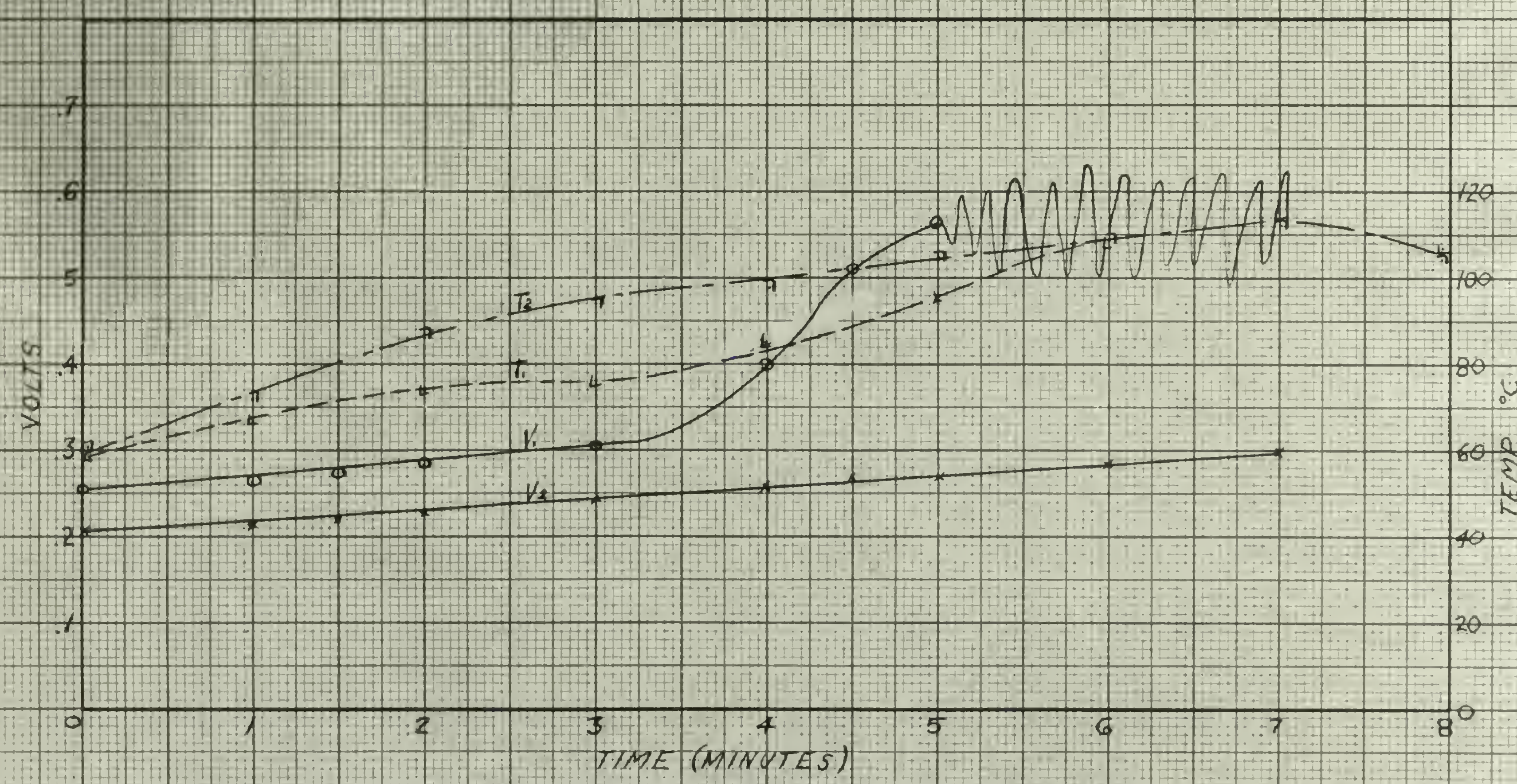
VOLTAGE DROP DUE TO CONTACT RESISTANCE VS CURRENT AT 6000 RPM

FIG 16



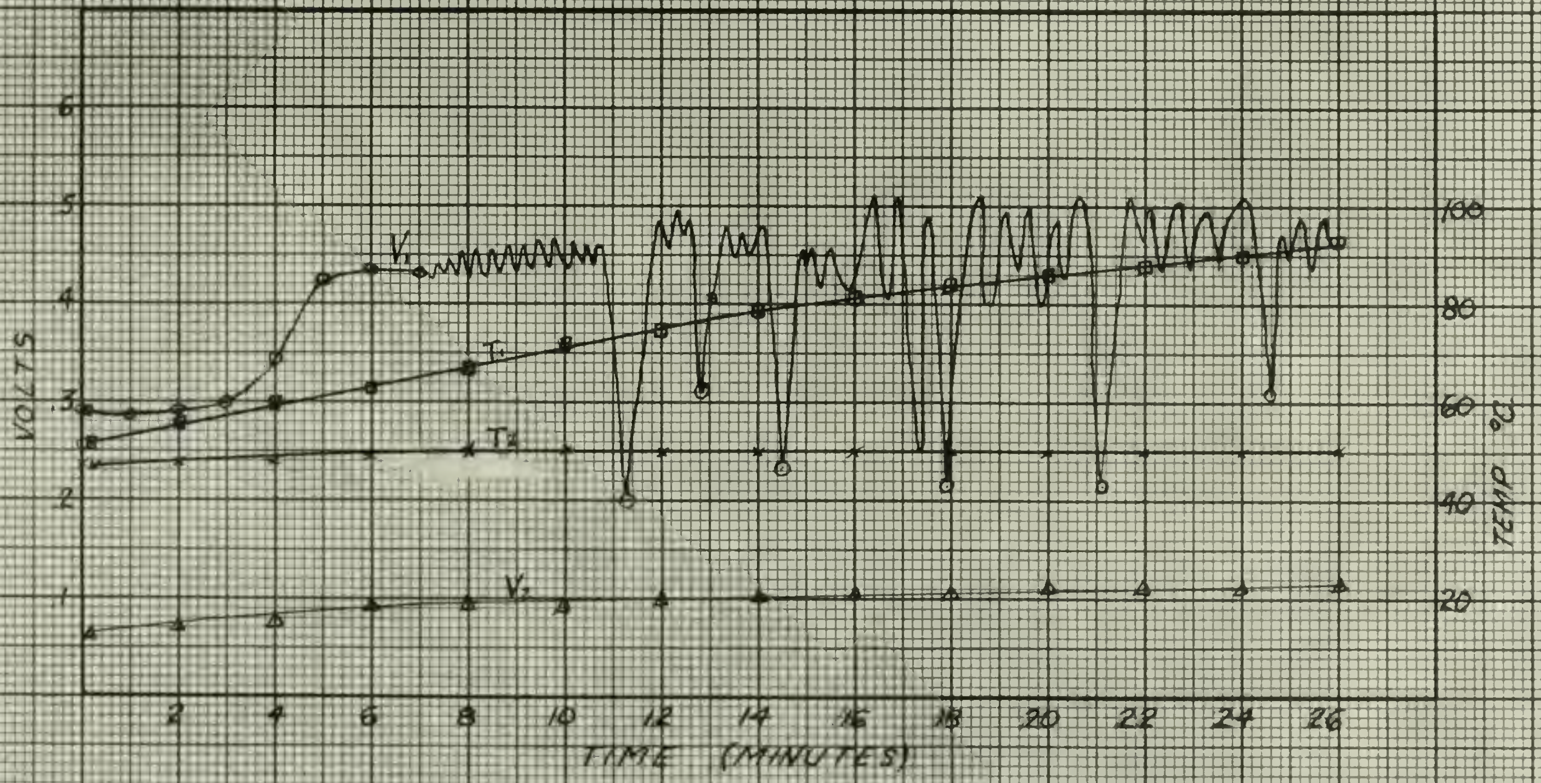
VOLTAGE DROP DUE TO CONTACT RESISTANCE VS CURRENT AT 8000 RPM

FIG 17



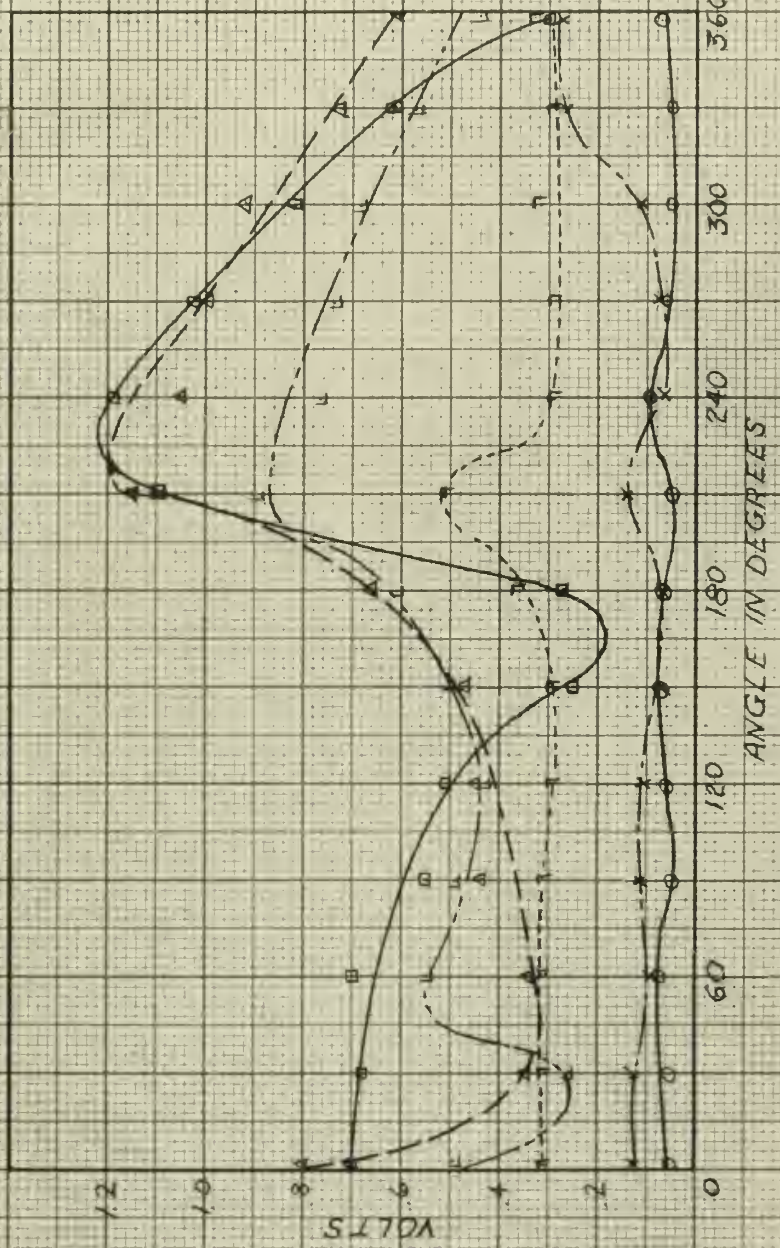
VOLTAGE DROP AND TEMPERATURE VS. TIME AT 300 AMPERES

FIG 18



VOLTAGE DROP AND TEMPERATURE vs. TIME AT 100 AMPS

FIG. 19



VOLTAGE DROP VS. ANGULAR POSITION AT 50 AMPERES

FIG. 20